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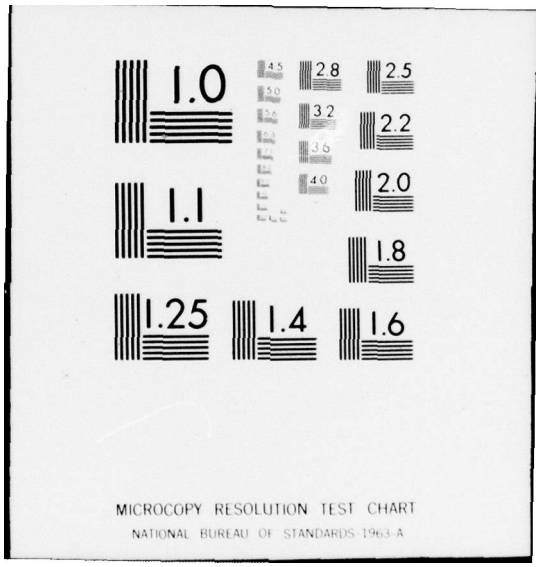
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ONR LONDON CONFERENCE REPORT

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XIIIth INTERNATIONAL SEMICONDUCTORS CONFERENCE (1976)

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3 MARCH 1977

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

The major topics of this conference were generally the same as those emphasised at the two previous conferences (Stuttgart, 1974, and Warsaw, 1972). We review the following subjects which were of particular interest at this meeting: surfaces and interfaces, excitons and exciton condensation, disordered semiconductors, and future semiconductor devices. In addition, selected presentations concerned with impurities, lattice dynamics, band structure, and one- and two-dimensional systems are also summarised.

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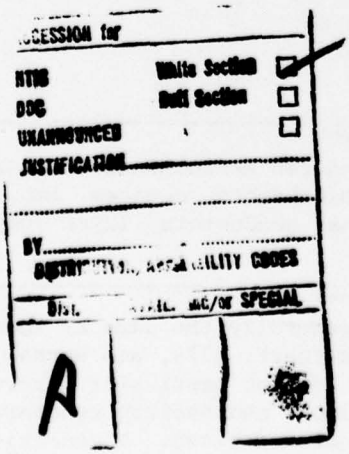
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XIIIth INTERNATIONAL SEMICONDUCTORS CONFERENCE (1976)

General Comments

In spite of trepidation on the part of a number of participants, the XIIIth International Conference on the Physics of Semiconductors, Rome, Italy, 30 August - 3 September, 1976, went off as planned and was generally a well-organized and efficiently run Conference. The only widespread grumblings heard around the Auditorium della Technica, the site of the lecture halls, concerned the luncheon arrangements. The wine was plentiful, but the food left something to desired.

Clearly, the best bargain in the city was the fare of the Metropolitana, 50 lire (∿ 6 cents at the time of the Conference) from the center of Rome to EUR, a ride of approximately 15 minutes.

We thought the distribution of the Conference participants among the various countries throughout the world quite interesting. As a means of measuring this, we take the numbers from the list of preregistered participants. The top 6 countries were: USA - 110; Federal Republic of Germany - 101; France - 86; Italy - 64; United Kingdom - 52; and Japan - 40. A total of approximately 600 participants were preregistered. With the exception of Italy, the host country, these numbers give some indication of the relative amount of semiconductor research throughout the Western world. Japan is rated somewhat low and Western Europe somewhat high with respect to the US by this sort of numbers game due to the travel costs involved. However, it is significant that the US representation was less than 1/3 that of Western Europe, and that this ratio represents a real trend in basic research in Semiconductor Physics. This trend is part of a general upsurge of quality research in solid state physics in Western Europe, particularly the Federal Republic of Germany. As usual, the representation of the USSR and Eastern Block countries was much less than their research efforts would warrant; for example, there were only 10 preregistered participants from the USSR.

The topics of most interest at this Conference were generally the same as those emphasized at the 1974 and 1972 meetings. These included, among others, Semiconductor Surfaces and Interfaces, Electron-Hole Drops and Excitons, Disordered Semiconductors, Transport and Magneto-Transport including Hot Electrons, Small Gap Materials, Band Structure, Rocombination and Luminescence, Optical and Magneto-Optical Properties, and Electron-Phonon Interactions.

At a conference of this size with 4 simultaneous sessions except for the plenary sessions, it is impossible to cover and summarize everything. Thus the topics discussed below represent a rather sub-

jective selection of those areas that the authors felt were most interesting and exciting, or were the most heavily emphasized.

Surface and Interface Properties of Semiconductors

At this Conference, even more than at the 1974 Conference at Stuttgart, a major area of emphasis was the physics of semiconductor surfaces and interfaces. Three of the thirteen plenary invited talks, four of the fifteen additional invited talks, as well as the twelve contributed papers and eight read by title were concerned with this general topic.

In the second plenary invited talk of the Conference, Dr. J.C. Phillips (Bell Laboratories) discussed the structure and properties of semiconductor surfaces. Phillips made some interesting contact between semiconductor surface physics and semiconductor crystal growth. Initially he reviewed some experimental techniques used to study semiconductor surfaces, results of these measurements, and limitations of the techniques. Low Energy Electron Diffraction (LEED) studies have shown that semiconductors can have large surface unit cells (reconstructions) and that phase transitions among different surface structures take place at temperatures T_c much lower than the bulk melting temperature T_f of the material. However, it is extremely difficult with LEED to extract information about the positions of the atoms within the reconstructed unit cell. Photoemission studies yield information about the valence band spectrum within about 5 Å of the surface (for photon energies of about 25 eV). A problem with this technique, with regard to specific surface information, is that the oscillator strengths of the dangling surface bonds is small. Covalent surface atomic configurations are thus difficult to resolve. At the cost of additional experimental complexity, angular resolved photoemission spectroscopy can be used to separate out the surface states. This was discussed in more detail in a later invited paper by J.E. Rowe (Bell Laboratories). Phillips also pointed out that a technique developed by H.D. Hagstrum (Bell Laboratories), and the subject of a contributed paper, "Ion Neutralization Spectroscopy," is sensitive to the surface layer of atoms only.

Phillips then went on to indicate the difficulties of calculating the band structure of surfaces, even with the simplifications that can be obtained with the pseudopotential method. Theoretically, one can calculate the energy positions of the surface states which come from the dangling bonds. The latter are formed when the bulk structure is interrupted. These have been done by different methods assuming that there is no surface reconstruction or relaxation. The general conclusion is that the surface bands lie higher than is found to be the case in the photoemission experiments. The simple explanation for this result is that the bond strength associated with the dangling bonds has been transferred partially to the back bonds. Thus in the

simple case of the most stable planes (Si and Ge (111) surfaces), the back bonds are strengthened to become closer to Sp^2 hybrids by relaxation of the first surface plane by $\sim$ 0.3 Å closer to the second surface plane. This increases all the bond interactions and pushes the calculated surface states below the top of the valence band. Phillips then described a strong interaction model explanation of the reconstructed surfaces of Si and Ge due to Lander who found that trace amounts of impurities stabilized reconstructions other than those found with clean surfaces. He sought a fundamental building block, which turned out to be a 2 x 2 unit itself stabilized by surface vacancies, which by assembling in "super-super-attices" could reproduce all observed reconstructions.

Drawing upon the previous discussion, Phillips also pointed out a rather interesting connection between semiconductor surface physics and crystal growth. In semiconductors, both the electronic and atomic structure are important in cyrstal growth. The growth is determined by competition between the metallic plasma energy and chemical bonding, subject to packing constraints and the discontinuity at the surface. He also noted that growing a semiconductor crystal from the melt is different than most other crystals for another reason. For semiconductors

ρ (semicond. liq.) $\tilde{\sim}$ 1.15 ρ (semicond. - crystal), while, for metals,

ρ (metal liq.) $\tilde{\sim}$ 0.95 ρ (metal - crystal) where ρ is the density. Thus for semiconductors there is always plenty of material for growth at the surface.

It has also been observed that certain reconstructions on cleaved surfaces are stabilized by steps and that high step densities suppress formation of reconstructions on low-index surfaces (within about 50 - 75 Å of steps) probably due to strain fields. The nature of step-step interactions is important in understanding the kinetics of crystal growth. Experimentally steps condense into risers ($\sim$ 500 Å in height) which are separated by terraces. This implies an attractive interaction between steps whose range can be estimated to be $\tilde{\sim}$ 75 Å from the angle of inclination of rise to terrace. It is observed that on Ge, Si and III-IV semiconductors risers are formed only on surfaces that reconstruct. If one takes the Lander model and assumes that reconstructed surfaces often involve surface vacancies, then as a riser sweeps across the surface during crystal growth by liquid-phase epitaxy, for slow enough growth, some of these vacancies could be retained in the bulk. The vacancy concentration could change abruptly from "slow growth" to "fast growth." Phillips concluded by suggesting that the concentration of vacancies and other defects may exceed equilibrium values by several orders of magnitude because of the kinetics of growth on reconstructed surfaces.

The subject of Surface Reconstruction in Semiconductors was discussed in more detail by E. Tosatti (University of Rome) in

another plenary invited talk. He reviewed some of the current models of surface reconstruction, concentrating on saturation of surface bonds as a reason for reconstruction (super-lattice formation). Tosatti also discussed two-dimensional charge density waves (CDW) as an example of surface bond saturation and their relation to surface reconstruction. There remain some problems with both the CDW model and the Lander vacancy model with respect to experiment. He concluded that for small-surface unit cells and strong deformation the chemical picture is most appropriate, which for large-surface unit cells and weak deformation the CDW picture is most appropriate.

Approximately 8 - 10 years ago, a substantial amount of work was carried out, particularly by the group at IBM, concerned with properties of quantum space-charge layers in Si metal-oxide-semiconductor (MOS) structures. After a brief period of quiescence, there has been in the past few years a remarkable resurgence of effort in this area. This is largely a result of the growing interest in the fundamental electronic properties of surfaces and interfaces in general, but two specific reasons underlie this interest as well: (1) the fact that the technology of producing good interfaces on Si has substantially progressed since the early work thus allowing experiments to be done and effects to be seen which were not previously possible; and (2) the application of the tools of far infrared optical and magneto-optical spectroscopy to the study of the high-frequency conductivity of these quasi two-dimensional conducting layers. The fact that two invited talks and two full sessions were devoted to this subject is an indication of the widespread interest.

In a plenary invited talk, F. Koch (Technical University of Munich) summarized the extensive work of the Munich group on spectroscopy of surface space-charge layers. The large electric fields achieved in MOS structures lead to a potential well in the semiconductor at the semiconductor-insulator interface which is sufficiently deep and narrow (several tens of angstroms) to lead to quantized levels at low temperatures (the electric field sub-bands) for motion perpendicular to the surface. Characteristic separations of these energy levels are of the order of 10 meV (in the far infrared), and electric dipole transitions are allowed for light with the electric vector polarized perpendicular to the interface. The Munich group has pioneered in the optical absorption spectroscopy of the inter sub-band levels which were originally observed optically via photoresistance measurements by Wheeler *et al* at Yale University. Recent results indicate that a simple interpretation of the maxima of the optical absorption spectra giving the sub-band splittings is not correct due to "depolarization" effects since the space-charge layer has finite thickness. This was the subject of a contributed paper by S.J. Allen and D.C. Tsui (Bell Laboratories). This means that the excellent agreement between the observed resonances and sub-band splittings, calculated with many-body

effects, must be regarded as fortuitous. Koch also discussed far infrared cyclotron resonance results in Si inversion layers on all three principal surface orientations as well as some interesting new cyclotron resonance data on 100 Si inversion layers as a function of uniaxial stress and temperature. These latter measurements show a very large enhancement of the mass at high temperatures and high stress and low densities which is presently unexplained.

In another invited talk J.J. Quinn (Brown University and Naval Research Laboratory) reviewed the theoretical situation with regard to many-body interactions in quasi two-dimensional systems. Quinn concentrated on the electron-electron mass enhancement as apparently observed in Shubnikov-de Haas experiments, as well as the possibility of such mass enhancement being observable in cyclotron resonance due to electron-impurity scattering and the occurrence of strong "harmonics" in the cyclotron resonance experiments.

In the contributed sessions two groups presented independent experimental evidence for the possibility of an electronic phase transition in very low-density (100) Si inversion layers. Iatayama *et al* (Hitachi Ltd., Tokyo) interpreted a conductance enhancement near threshold (low electron densities) which peaked sharply at 13 K in terms of a Wigner crystallization. Wagner *et al* (Naval Research Laboratory) suggested the possibility of an electronic phase transition to explain a dramatic line narrowing of far infrared resonant magneto-absorption observed at low densities and high magnetic fields.

Some remarkable results were reported by R. Dingle (Bell Laboratories) in his invited paper on optical properties of semiconductor superlattices. These are thin repeated semiconductor heterostructures ($GaAs\text{-}Ga_{1-x}Al_xAs$), grown by molecular beam epitaxy. Individual layer thicknesses ranged from $\approx$ 3 Å (essentially a single monolayer) to about 500 Å, and single structures contained as many as 10^4 layers. The optical absorption and emission data were analysed through the use of simple one-dimensional quantum mechanical models that included size quantization of both electrons in the conduction band and holes in the valence band. These results indicate the possibility of tailoring structures on a microscopic scale.

Amorphous and Disordered Semiconductors

The area of amorphous and disordered semiconductors received about as much emphasis at this Conference as at the preceding one in Stuttgart. There were two sessions devoted to this topic which included 13 contributed papers and one invited paper. In addition, the opening plenary invited talk was given by Professor N.F. Mott (University of Cambridge) on this same subject. In his presentation, Mott assumed that the amorphous semiconductor could be described by a continuous random network model in which all bonds are satisfied.

He then argued against models (such as the CFO model) which involve measurable densities of localized states deep within the gap, other than those due to specific point defects such as dangling bonds or impurities. The familiar picture of charge transport at low temperatures by hopping between localized states, $\sigma \propto \exp(-B/T^{+1/4})$, and at high temperatures by the movement of electrons excited to the mobility edge, $\sigma \propto \exp(-E/kT)$, was described in some detail.

Schematic plots of the conductivity, the Hall mobility, and the thermopower as functions of temperature were presented, and the effect of the transition from hopping to band edge conduction was described in each case. At high temperatures the temperature-independent Hall mobility can be estimated using a theory developed by L. Friedman (University of St. Andrews), but Mott suggested that the fall-off of the Hall mobility at low temperatures was due to the change from charge transport at the mobility edge to hopping. Mott also reviewed his concept of a "minimum metallic conductivity" ($\sigma_{min} \sim 300\text{-}10000\Omega^{-1}cm^{-1}$), although he observed that its existence was still somewhat controversial.

A major portion of Mott's opening presentation concerned the question of whether or not the small polaron concept (as espoused by D. Emin, Sandia Laboratories) was relevant to charge transport mechanisms in amorphous materials. His conclusion, which he acknowledged to be rather controversial, was that self-trapped holes (similar to V_k centers in the alkali halides) are important for charge transport in some oxide glasses such as SiO_2, but that the small polaron concept is inappropriate for the chalcogenides.

Mott mentioned the success of W.E. Spear and P.G. Le Comber (University of Dundee) in doping amorphous Si, but suggested that the chalcogenides will not be as susceptible to doping with shallow impurities as the tetrahedrally-coordinated amorphous solids. Most participants agreed with this assessment. For the chalcogenide glasses, Mott described the evidence for the pinning of the Fermi energy gap (MDS model), first proposed by himself, R.A. Street (Xerox, Palo Alto Research Center) and E.A. Davis (University of Cambridge). An alternative model developed by M. Kastner (MIT), D. Adler (MIT) and H. Fritzsche (University of Chicago) {see *Phys. Rev. Lett.* 37, 1504, (1976)} was mentioned by Mott as providing "important modifications" to the original MDS model. Mott concluded by discussing how the MDS model could be modified to explain the dramatic changes in the magnitude and activation energy of the conductivity in amorphous Se upon doping with O as observed several years ago by W.A. LaCourse (Alfred University), V.A. Twaddell and J.D. MacKenzie (University of California, Berkeley) [*J. Non-Cryst. Solids* 3, 235 (1970)], and the changes observed in the luminescence by Street. This explanation assumes that the oxygens bond preferentially to the negatively charged defects (D^-, in Mott's notation).

After his presentation, Mott was asked by F. Williams (University of Delaware) about the evidence for the existence of charged defect centers in the chalcogenide glasses as assumed in the MDS model. Williams pointed out that one can get strong temperature dependences of the luminescence in crystalline semiconductors for neutral centers.

In the other invited paper on amorphous semiconductors, Spear described his measurements (with Le Comber) on doping of P and B into amorphous Si and Ge deposited by decomposition of silane or germane. In evaporated amorphous films of Ge or Si, the density of states within the gap is everywhere too great to be altered by doping except for a shift of the Fermi level toward the conduction band. However, when amorphous Si or Ge are made by the decomposition of silane or germane, the magnitude of the density of states drops by over three orders of magnitude and doping with P or B results in dramatic changes both in the density of states as measured using the field effect and in the conductivity. Variations in the room temperature conductivity between 10^{-2} and 10^{-12} Ω^{-1} cm^{-1} for both n- and p-type samples were presented for P and B-doped α-Ge and similar results were quoted for amorphous Si. In a typical n-type material, approximately 30% of the phosphorous atoms in the amorphous network act as donors. The roles of the remaining 70% remain unknown. Spear also presented data on the Hall mobility as a function of temperature and doping and described an all-amorphous silicon p-n junction. At the conclusion of the presentation, Professor W. Paul (Harvard University) asked several questions concerning the role of the surface states both in determining the doping efficiency and in interpreting peaks in the density of states as determined by the field effect measurements.

Further measurements on doped amorphous Si (photoluminescence and photoconductivity) were presented by R.Fischer representing the group at the University of Marburg (paper of W. Rehm *et al*). These authors, who also prepared films by decomposition of silane, obtained PL peaks at 0.8 eV for both P and B doping which were shifted from the 1.2-eV peak observed in the undoped materials. The photoconductivity is also affected by P and B doping. After this paper Paul commented that similar doping effects had been observed by the group at Harvard using sputtering techniques.

The important research of G. Pfister, H. Sher and E.W. Montroll (Xerox Webster Research Center) on time-dependent electrical transport in amorphous semiconductors was discussed by Pfister. He showed that the peculiar time-of-flight measurements in amorphous Se and As_2Se_3 can be related simply to the statistics which describe the dynamics of the propagating carrier packet and are independent of the details of the microscopic transport mechanisms. Specifically, one can generate a master plot (for different field strengths and sample thicknesses) of the relative current I(t) as a function of time normalized to the

transit time t_T for the case where the microscopic transport mechanism is characterized by a broad distribution of individual event times. For $t < t_T$, the current has the time dependence $t^{-(1-\alpha)}$, and for $t > t_T$ the dependence $t^{-(1+\alpha)}$ where $0 < \alpha < 1$. Specific experimental results for Se and As_2Se_3 were presented by Pfister and compared with the predictions of the Sher-Montroll stochastic model. He cautioned that there is a distinct difference between the drift mobility and the dc mobility in this interpretation. He suggested that the microscopic transport mechanism in As_2Se_3 was trap-controlled hopping and in Se either hopping or extended-state conduction.

T.L. Reinecke (Naval Research Laboratory) discussed a new theoretical approach to explain photostructural and photodarking effects in amorphous semiconductors (paper of K.L. Ngai *et al*). This approach employs a model Hamiltonian and couples the photo-excited electrons to those low lying atomic or ionic tunnelling modes which are thought to be responsible for the anomalous low-temperature thermal properties of glasses.

P.C. Taylor reviewed the recent work of the Naval Research Laboratory group on metastable, paramagnetic states in the gap in amorphous semiconductors (paper of S.G. Bishop *et al*). Taylor also described certain compositional trends of the ESR and optical absorption measurements and discussed the temperature dependence of these metastable states in As_2Se_3.

J.E. Fischer *et al* (University of Pennsylvania) described an extension of the van Vecheten-Bergstresser theory of the band structure of alloys to nonisovalent alloys such as PbS-CdS and GaP-ZnSe. A. Willing and B. Sapoval (Ecole Polytechnique) presented a simple molecular model which accounts well for the observed Te NMR chemical shifts in crystalline compounds and gives a qualitative explanation for the changes in Te^{125} NMR chemical shifts which occur between the crystalline and amorphous phases.

Impurities

Studies of the physics of impurities and defects in semiconductors received less emphasis at this Conference than at previous ones with one invited paper and eight contributed papers specifically identified as impurity related plus six papers, mostly concerned with luminescence via impurities, in two other sessions. In comparison, there were three invited papers and thirteen contributed papers on this topic at the Stuttgart Conference. This may not be a fair representation of the interest in impurity and defect studies in the semiconductor community since there was a conference in Yugoslavia, immediately after the Rome Conference which was specifically devoted to defects in solids. In fact, there is currently a great deal of

fundamental as well as technological interest in deep level impurities in semiconductors in general, and in the III-V compounds in particular.

In his invited paper on thermochemical properties of impurities and other defects in semiconductors, Dr. J. van Vechten (IBM, Yorktown Heights) presented a general "shopping list" of impurities, defects, and related processes, about which little is known. These include: recombination enhanced diffusion, the swirl defect in Si wafers, stoichiometry deviations (vacancies, anti-site defects), and gold in Si. While pointing out that progress is being made with molecular orbital and other tight binding cluster calculations, as well as with pseudopotential methods, van Vechten made a strong case for the thermochemical approach as practiced by himself and others since this approach can provide simple estimates and delineate chemical trends for classes of defects. One of the most interesting aspects of his talk concerned anti-site defects in III-V compounds (e.g., phosphorous on a gallium site in GaP) which van Bechten has estimated should be energetically easy to form in large concentrations. There is now some fairly strong experimental evidence (from ESR of P in GaP by Schneider *et al* Institut für Angeuandte Festkorper Physik, Freiburg) that such anti-site defects exist in fairly large concentrations ($> 10^{16}$ cm^{-3}) in GaP.

Among the contributed papers P.J. Lin-Chung and B.W. Henvis (Naval Research Laboratory) and A. Baldereschi and N.O. Lipari (Laboratory of Applied Physics, Lausanne and Xerox Webster Research Center) presented improved calculations of acceptor states in diamond-and zinc-blende semiconductors. The properties of deep centers were investigated theoretically by several authors using both cluster calculations and the pseudopotential approach, and H.J. Stocker and M. Schmidt (Max Planck, Stuttgart) and W. H. Doschel *et al* (Naval Research Laboratory) presented some fairly detailed photoluminescence studies of the nature of deep levels caused by transition metal doping (Cr andFe) of GaAs and InP.

Exciton Condensation

At low temperature and under high optical excitation, electrons, holes and excitons in quite pure Ge and Si condense into "metallic" droplets of "electron-hole liquid" typically of the order of microns in size. Over the past six years or so there has been very extensive experimental and theoretical work on this phenomenon, both because of the interest in the properties of semiconduictors under high optical excitation and also because the high-density "electron-hole liquid" is in many ways an ideal system in which to test theories of the interacting Fermi gas. As at the previous semiconducters conference at Rome there was a large emphasis on this topic. Two full sessions and two invited lectures were devoted to electron-hole droplets, and there were several other sessions partially devoted to this subject. Many new results in this area were presented, and there was much

informal discussion of this subject. Several important new developments were reported, some of which are noted below.

The conditions under which a single large drop of the order of mm in size (as opposed to a "cloud" of smaller drops) can be produced was clarified, after several years of controversy, in an invited paper by C.D. Jeffries (University of California, Berkeley) and in a contributed paper by Ya. Pokrovsky and K.I. Svistunova. Such large drops are found to form only under high optical excitation in a region of Ge or Si in which there is a large inhomogeneous, uniaxial strain; this strain reduces the effective band gap in that region of the crystal which allows the drop to form there. High local optical excitation without such a strain produces a dense cloud of small ($\sim \mu$) drops. The appearance of the large drops for the stressed case has been inferred from abrupt changes in (i) the electron-hole recombination time, (ii) probe laser absorption, (iii) small-angle light scattering, and (iv) microwave resonance under the application of strain. Further, calculations of the effect of the inhomogeneous strain on the binding energy and density of the electron-hole liquid as a function of position in the large drop agree well with observed recombination luminescence.

The observation of electron-hole drops in a variety of semiconductors other than the widely studied cases of Ge and Si (e.g., in polar and direct gap materials) was reported. G. Beni and T.M. Rice (Bell Laboratories) included electron-LO phonon coupling in calculations of the electron-hole liquid ground-state energy and predicted the appearance of droplets in certain polar semiconductors. Evidence for such droplets in CdS, CdSe, and AgBr was reported by R.F. Leheny and J. Shah (Bell Laboratories) based on gain and absorption measurements of a tunable probe laser beam after high optical excitation. Evidence for electron-hole droplet condensation was reported also for Te by H. Miyanchi and Y. Nishma (Tohoku University) and for GaAs by O. Hildebrand and E. Göbel (University of Stuttgart).

An interesting possibility was contained in a report of weak resonant absorption of ultrasonic waves (by electron hole drops) in Ge by J.Y. Prieur *et al* (University of Paris). They tentatively ascribe this absorption to excitation of shape oscillations of the droplets which allows them to estimate the droplet surface tension from their measurements. This approach may eventually provide a fairly direct measurement of the droplet surface tension which is a very important parameter from the theoretical point of view. It also represents the first report of a surface-type of collective droplet mode.

Lattice Dynamics

One session comprising eight contributed papers was devoted to lattice dynamics. In addition, R.M. Pick (University of P. an

M. Curie, Paris) presented an invited paper on lattice dynamics and phase transitions in which he reviewed recent theoretical developments on both displacive and disordered transitions frome a dynamical point of view. In a contributed paper R.M. Martin and D.J. Chadi (Xerox Palo Alto Research Center) described a method of calculating angular bond-bending forces directly from electronic energies in diamond- and zinc-blende structure crystals. In this method electrons and phonons are treated within the framework of identical approximations. R. Zeyler *et al* (Max Planck Institut, Stuttgart) described the extension from ionic crystals to covalent semiconductors of a specific bond-charge model which assumed weak Coulomb forces between the bond changes and a valence force field for the short range force. Multiphonon spectra of tetrahedral semi-conductors were discussed by S.S. Mitra (University of Rhode Island) who concluded that almost all of the observed features are a direct consequence of structure in the one phonon (harmonic) density of states and are not particularly influenced by multiphonon selection rules (paper of B. Bendow *et al*). J.D. Joannopolous and R.B. Laughlin (MIT) presented a force constant model of phonon modes at crystalline and amorphous tetrahedrally bonded surfaces. They emphasized that with this model exact solutions are obtained for the local phonon densities-of-states on surface atoms.

One- and Two-Demensional Systems

One plenary invited talk and six contributed ones were concerned with the topic of one- and two-dimensional conductors. The most popular materials included the often exploited but seldom understood quasi-one-dimensional organic conductor TFF-TCNQ and the polymer polysulfur nitride $(SN)_x$. In his plenary invited presentation, Professor H. Kamimura (University of Tokyo) showed a table of Drude parameters for $(SN)_x$ which indicated good agreement among the groups at Tokyo, Cambridge, IBM San Jose, and Karlsruhe, but clearly showed disagreement by several orders of magnitude between these groups and the result of the Pennsylvania group. The fact that this table represented vividly the explosively chaotic and polarized development of this sub-field over the past few years was not lost on the audience. Kamimura went on to describe $(SN)_x$ as a semi-metal and TTF-TCNQ and KCP as quasi-one-dimensional metals. He explained that, in the tight binding picture, the differences between these two types of materials depend on the s-p mixing which determines the relative strength of the interchain interaction. In contributed presentations, J.S. Blakemore et *al* (Florida Atlantic University) described the transport properties of $Cs_2(TCNQ)3$ and B. Walker *et al* (IBM Yorktown Heights) discussed the reflectance of TTF-TCNQ at high pressures. Electrical properties of $(SN)_x$ were reported on by H. Kahlert and K. Seeger (University of Vienna).

Layer Compounds were the subject of two sessions at the Conference (one invited and ten contributed papers). F.J. Di Salvo (Bell Laboratories) gave an invited presentation on charge-density

instabilities in layered compounds and discussed $TaSe_2$ as a specific example. Di Salvo argued against the suggestion of E. Tossatti and P.W. Anderson (*S.S. Commun.* 14, 773, (1974)) that charge-density waves might explain some of the surface reconstruction in Si and Ge, and he cited the presence of strong local bonding forces and the lack of reversibility with temperature as evidence against the presence of charge-density waves on surfaces of Ge and Si. Various compounds in the system GaS_xSe_{1-x} were the subject of contributed talks by J. Camassel *et al* (University of California, Berkeley), C. Depeupsinge and L.C. Thanh (Laboratory of Applied Physics, Lausanne), and A. Polian *et al* ((University of P, and M. Curie, Paris). P.G. Harper (Heriot-Watt University) and K. Maschke *et al.* (Laboratory of Applied Physics, Lausanne) discussed layer warping and stacking disorder, respectively, in layered semiconductors. Finally, the band structure of graphite and the electronic and lattice properties of intercolated graphite were the subjects of papers by H. Nagayoshi *et al* (University of Tokyo) and D.D.L. Chang *et al* (MIT), respectively.

Band Structure

Fundamental studies of the band structure of semiconductors are receiving considerably less emphasis recently since this is a rather mature area. For example, there were only two theoretical papers concerned with band structure presented at this Conference. W. Harrison (Stanford University) presented a review of the theory of covalent, polar and ionic solids. He related the NFE (nearly-free-electron) theory to the LCAO (linear combination of atomic orbitals) theory by identifying conceptually and quantitatively the interatomic matrix elements in the LCAO with the pseudopotential form factors in the NFE theory. The appropriate expansion parameter in the approximate theories is the ratio of the pseudopotential to the Fermi energy for metals. It is the inverse ratio for insulators. Thus, instead of including higher order pseudopotentials, a different expansion is required for the band structure of insulators. In a contributed paper by F. Aymerich *et al* (Cagliari and CNR, Lausanne) an alternate general-model pseudopotential was adapted to calculate the band structure of tetrahedral semiconductors. These authors introduced three parameters in their new expression for the model potentials. Experimentally, the dominant effort was involved with studies which utilized UV photoemission spectroscopy in some form, particularly using synchrotron radiation as a source, or angularly resolved photoemission.

Semiconductors in Applications

An indication of the increasing concern in the semiconductor community over contact of the research with applications was the inclusion of an entire Plenary Invited Session of five talks on the topic, "Semi-

conductors in Applications." Dr. L. Esaki (IBM, Yorktown Heights) gave a review of the highlights of semiconductor device development in a historical context. He described a number of significant scientific achievements and their applications, in perspective. Esaki suggested that it has been a cyclical feed-forward, feed-backward situation in which large-scale semiconductor-device development efforts made available the most desirable semiconductor materials and structures. This, in turn, enabled physicists to perform a number of novel experiments, which led to some important discoveries, and so on.

C. Hilsum reviewed the physics of various types of instabilities and hot electron effects and their application in devices such as the Gunn Diode, IMPATT, TRAPATT, FET, and TED. He pointed out the principles of operation and the advantages and disadvantages of the various devices, as well as suitable materials and materials limitations.

J.T. Wallmark (Chalmers University of Technology, Gothenberg) described the fundamental physical limits to large-scale integration. The major part of his analysis is based on the circuit connection pattern and is thus common to all types of integrated circuits. The major considerations are: (1) Minimum device line dimensions (ultimately in the several micron range) which are limited by the uncertainty principle, quality and yield requirements, doping variations, etc; (2) The maximum and minimum current densities which are influenced by electromigration, power dissipation and speed requirements; and (3) The minimum power per element. A fundamental limitation here is based on thermal motion of charge carriers.

Recent developments in heterojunction lasers were described by Dr. H. Kressel of RCA Laboratories, Princeton. A number of advances have been made in recent years and devices can now be obtained with emission ranging from about 10 μm to 0.6 μm. Kressel also pointed out that the area of defects is particularly important since they are frequently the determining factor in the operating lifetime of these devices.

The topic of semiconductors in solar energy conversion was addressed by B.O. Seraphin (University of Arizona). Seraphin pointed out what many others have said, namely, that solar energy will contribute to energy needs provided that the performance of existing devices can be improved, and most important, the cost can be substantially lowered. Problem areas involve materials and manufacturing processes. In addition, improved understanding of the optical processes in semiconductors at the elevated temperatures of a solar-thermal plant is necessary. Some interesting possibilities which are presently outside the mainstream are photoelectrolysis at semiconductor-electrolyte interfaces and other photochemical schemes, all of which involve poorly understood semiconductor interface physics.

Closing Remarks

In the tradition of previous conferences, the closing session was devoted to summary remarks, in this case by Dr. A. Frova of the University of Rome. As is the usual custom Frova initially commented on thdifficulty of the task that he had been assigned. He went on to remark, apparently as a plea to reduce the volume of literature in semiconductor physics, that a proliferation of data and mere knowledge of details doesn't necessarily increase understanding. He then summarized the changes in emphasis of the general research techniques over the period 1950-1976. Theoretical research has remained approximately at a constant level; techniques for investigating optical properties have been increasing with the advent of far-UV sources (synchrotrons) and photoemission spectroscopy; and transport studies have been de-emphasized. With regard to materials, work on Ge has dropped off; studies of Si, which first decreased, have recently increased with the interest in space-charge layers; investigations of III-V semiconductors are becoming more numerous, most likely driven by technological needs; and studies of small gap materials have been roughly constant in number. In different sub-fields, studies of impurities and defects and bands and bonds are presently receiving less emphasis; research on surfaces is becoming more important after going through a minimum in the early 60s; exciton studies are of increasing importance as a result of interest in high excitation conditions and electron-hole drops. Excitons and surfaces run nearly parallel over the whole period; both were fashionable in the pioneering days, went through a dormant period in the early 60s, and are now under intense investigation once again as mature fields.

Frova also mentioned that he saw a present trend toward the study of more fundamental physical parameters and away from applied work. This point is certainly subject to debate; it is our belief that much of the basic work reported at this Conference was driven by obvious technological needs for better performance, lower cost or higher reliability, e.g., III-V materials, defects, surfaces and interfaces, and hot electron studies.